Ultrasound for the Assessment of Respirator Fit*

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Objective

No widely applicable methods exist for monitoring fit while working in a respirator. Fit information obtained during use would aid in improving respirator efficacy.

Fluid leak detection is often carried out by measuring ultrasound that is either generated in situ by turbulent leak flow or admitted via the leak path from a source.

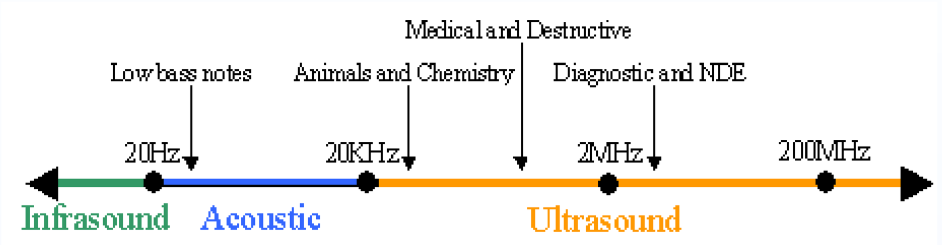
The objective is to determine if ultrasound techniques be applied to respirator leakage and the assessment of respirator fit?

Background

Ultrasound is defined as cyclic sound pressure with a frequency greater than the upper limit of human hearing (≥ 20 kilohertz). Ultrasound would not interfere with the respirator user.

As evidenced by the suggested TLV® guidelines published by ACGIH , exposure to airborne ultrasound does not generally pose a human health risk. (Table 1)

Applications of airborne ultrasound technology include ranging, tracking and positioning, the detection of fluid leaks, friction (e.g. bearing wear) and electrical discharges.



Frequency range corresponding to ultrasound

Table 1. TLVs for Ultrasound (ACGIH 2010)

Mid-Frequency of Third Octave band (kHz)	One-third Octave-Band Level In Air in dB Re: 20μPa; Head in Air	
	Ceiling Values	8-Hour TWA
10	105[A]	88
12.5	105[A]	89
16	105[A]	92
20	105[A]	94
25	110[B]	—
31.5	115[B]	—
40	115[B]	—
50	115[B]	—
80	115[B]	—

[A] Subjective annoyance and discomfort may occur in some individuals at levels between 75 and 105 dB.
[B] These values assume coupling with substrate (e.g. water) in the absence of coupling these thresholds may be raised 30 dB.

Ranging device
4" x 1.5" 5V

Leak detector with generator
9V

Transceiver
0.4" dia. x 0.1"
5V

Several features of ultrasound technology lend themselves to use with respirators: Transmitters and receivers are small in size, power requirements, and low cost. Furthermore, all techniques used with sound (e.g. spectral analysis) are applicable to ultrasound.

Ultrasound Source Assessment

As shown in Figure 1, turbulent flow occurs above the critical Reynolds number (typically 10^3 to 10^4). Ultrasound generated by turbulent flow is commonly used for leak detection. Table 2 gives the Reynolds number (Re) for representative conditions for respirator flow sources of nasal breathing, mouth breathing and a leak of 0.01 of the total respiration flow (Ve) which corresponds to a protection factor (PF) of 100. The flow in both the leak and mouth breathing are not turbulent and hence are not expected to give rise to ultrasound. However, the Reynolds number for nasal breathing (calculated at the nostril opening) readily exceeds the critical Reynolds number and (as measurements corroborate) nasal breathing produces readily detectable levels of ultrasound.

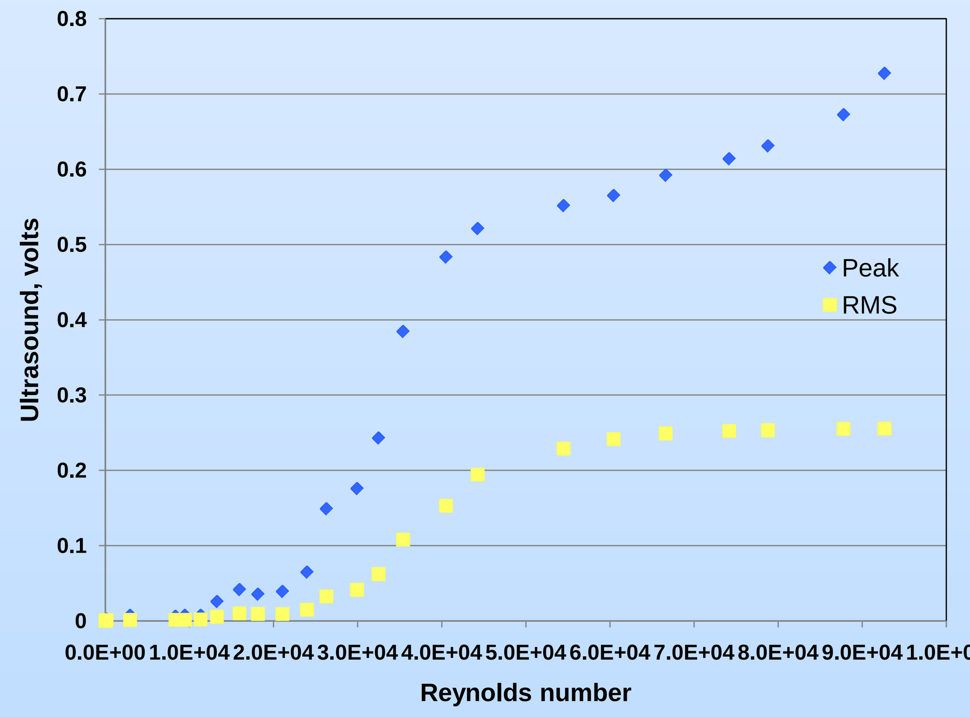


Figure 1. Upstream Ultrasound Intensity versus Reynolds Number

$$Re = \frac{\text{Dynamic pressure}}{\text{Shearing stress}} = \frac{\rho v_s^2/D}{\mu v_s/D^2} = \frac{\rho v_s D}{\mu} = \frac{v_s D}{\nu}$$

Relationship between Reynolds Number and Flow Conditions

Table 2. Reynolds numbers and conditions for some sources

Source	Re	V_s	D	v	μ	ρ	Ve	PF	W
units		m s^{-1}	m	m^2 s^{-1}	N s m^{-2} or Pa·s	kg m^{-3}	L·$min.^{-1}$		m
leak	2.4E+01	3.3	0.0001	1.37E-05	0.0000178	1.294643	20	100	0.01
nostril	3.4E+09	259.8	0.007	1.37E-05	0.0000178	1.294643	10		
mouth	8.2E+02	26.7	0.023	1.37E-05	0.0000178	1.294643	20		

Results

Ultrasound Magnitude versus Leak Size

The amplitude (intensity) of ultrasound passing through a leak would be expected to be proportional to the leak cross-section. To confirm this, the detector (shown above) was fitted with covers with various-sized circular holes. The ultrasound amplitude was measured with the detector at a fixed distance from the generator (see diagram on Figure 2). The results (Figure 2) show a direct proportionality between detected magnitude and hole diameter (adjusted R^2 = 0.91).

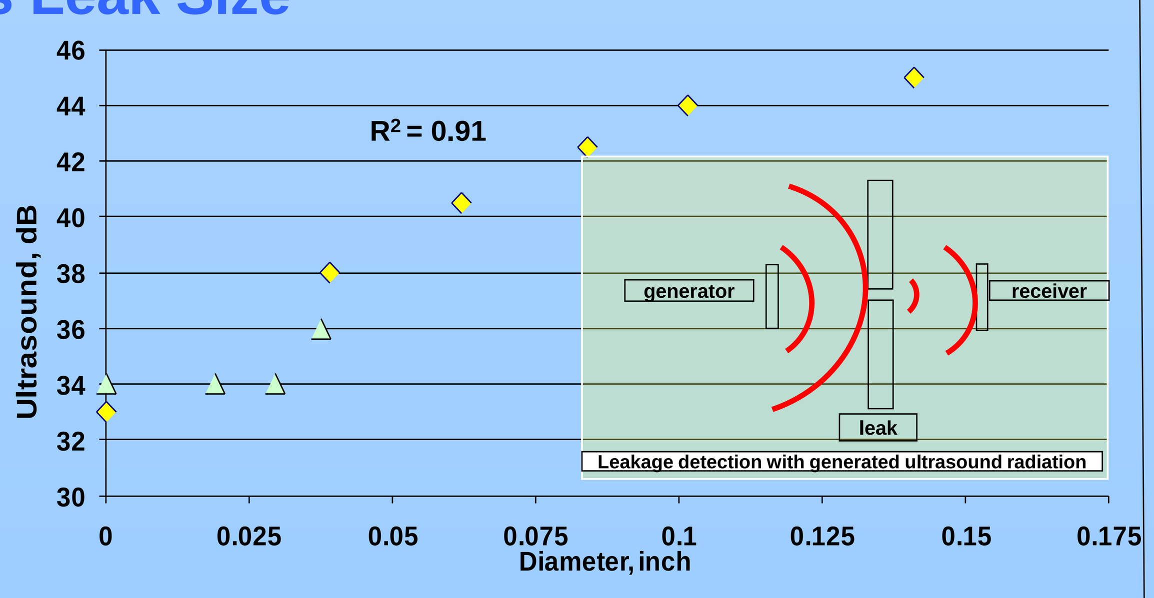


Figure 2. Amplitude versus Leak Size with Generator as Source

A similar experiment was performed using nasal breathing as the ultrasound source. There is a good correlation between hole-diameter and measured ultrasound for both exhalation and inhalation. (Figure 3)

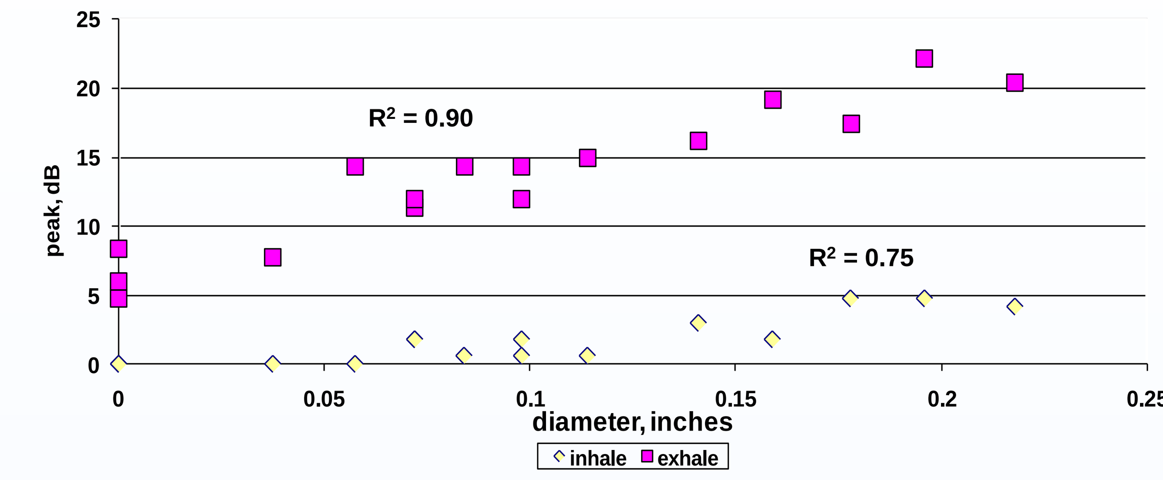


Figure 3. Amplitude versus Leak Size with Nasal Breathing as Source

Comparison with Fit in Half-mask Air-purifying Respirators

Respirators were fitted with sampling probes to allow the simultaneous measurement of fit factor with a TSI PortaCount. A single exercise/sampling period (one minute duration) was used to measure fit factor.

During the aerosol sampling period while the wearer breathed through the nose ultrasound levels outside the respirator were measured at five points around face seal: left side of the nose (below the eye), right side of nose, right cheek (proximal to the ear), left cheek, and under the chin.

To vary the degree of fit each respirator was measured three times using different head strap tensions: loose, tight, and very tight. The peak ultrasound measured at each point for inhalation and exhalation were averaged for all points and plotted versus the fit factor measured. Regression analysis showed a good correlation (R^2 = 0.79) between average peak ultrasound and fit factor.

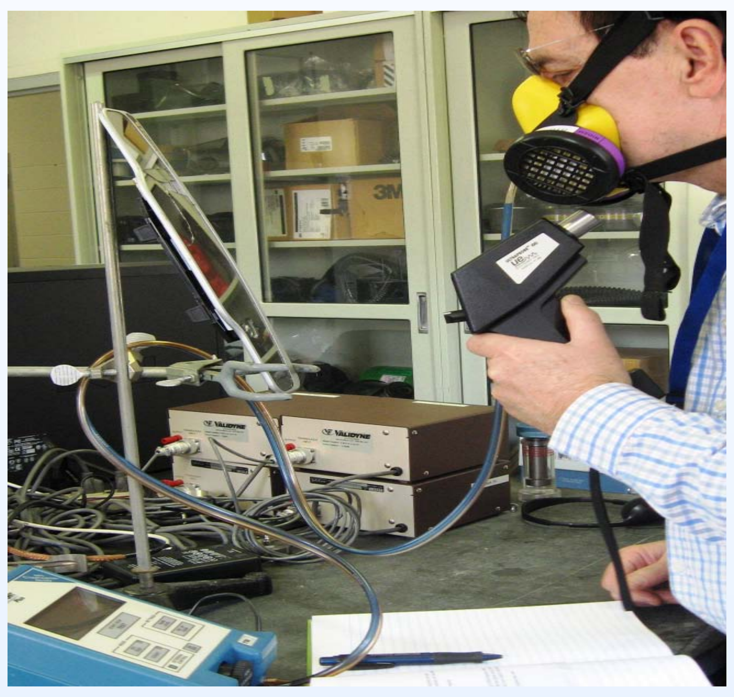


Figure 4. Simultaneous Measurement of Fit Factor and Ultrasound Leakage

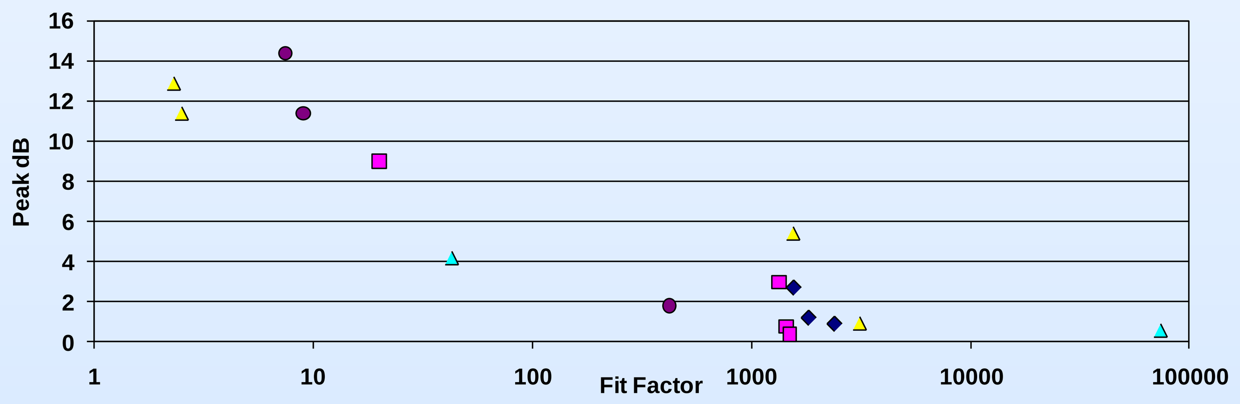


Figure 5. Ultrasound Leakage versus Protection Factor for Elastomeric Half-mask Respirators

Single tests were also performed with thirteen different N95 class filtering facepiece respirators. These results plotted below right show a moderate correlation (adjusted R^2 = 0.55) with fit factor.

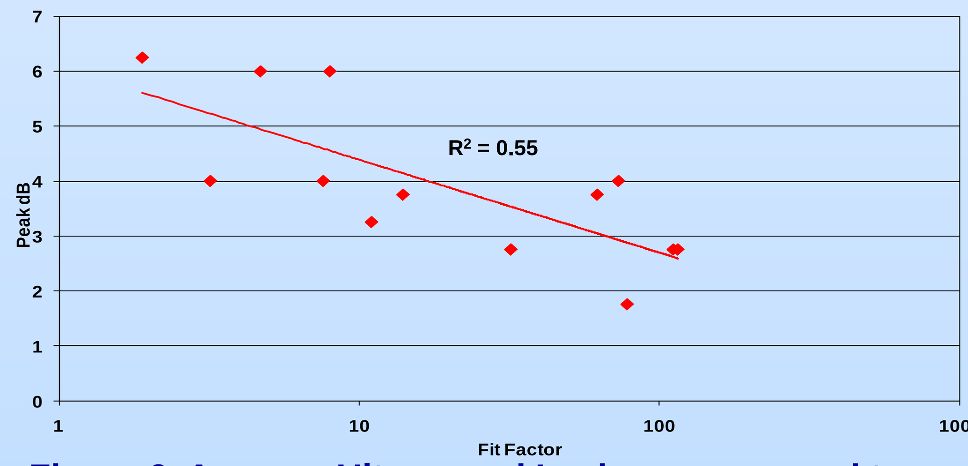


Figure 6. Average Ultrasound Leakage compared to Protection Factor for Filtering Facepiece Respirators

Conclusions

The magnitude of ultrasound penetrating through circular leaks (holes) is proportional to the diameter.

Leaks expected in air-purifying respirators are not likely sources of nascent ultrasound. Nasal breathing is a significant source of periodic ultrasound.

The average ultrasound leakage at the face seal (when using nasal breathing as the source) correlates with fit factor for half-mask respirators and filtering face piece respirators.

These results together with salient features of ultrasound technology indicate the potential to measure practically the status of respirator fit in situ using ultrasound.

Expected Outcomes

Development of a novel method to assess respirator leakage and respirator fit

Patent Pending: **Provisional patent application filed in the United States Patent and Trademark Office on April 30, 2010 and assigned US Serial No. 61/329,846**

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